ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPMF059

STATUS OF THE FCC-EE TOP-UP BOOSTER SYNCHROTRON

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Abstract

This contribution presents the status of the top-up booster synchrotron for the FCC electron-positron collider FCC-ee, which is a 100 km electron-positron collider being designed for precision studies and rare decay observations in the range of 90 to 365 GeV centre-of-mass energy. In order to keep the luminosity at a level of the order of $10^{35}\,\mathrm{cm^{-2}s^{-1}}$ continuous top-up injection is required, because of the short beam lifetime of less than one hour. The top-up booster synchrotron will be housed in the same tunnel as the collider rings and will ramp up the beam energy from 20 GeV at injection to the full energy between 45.5 GeV and 182.5 GeV depending on operation mode. The lattice design and two possible optics will be presented. The dynamic aperture was investigated for different sextupole schemes with and without misalignments of the lattice components. In addition, wigglers were installed to decrease the damping time and mitigate intra-beam-scattering.

INTRODUCTION

The very high target luminosities of the order of 10^{34} – $10^{36}\,\mathrm{cm^{-2}s^{-1}}$ lead to very short beam lifetime due to bremsstrahlung and radiative Bhabha scattering. As a consequence the FCC-ee injector complex foresees a full energy booster for continuous top-up injection in the same tunnel as the collider [1]. As the collider will be operated at four different beam energies ranging from 45.5 GeV to 182.5 GeV, this immediately defines the beam energies in the booster at extraction. The value of the injection energy is determined by the field quality and reproducibility of the magnetic field in the dipole magnets in the arc sections. In the current design an energy of 20 GeV is considered resulting in a magnetic field of $B = 6\,\mathrm{mT}$.

Apart from the booster, a 6 GeV linac, a damping ring and a 20 GeV pre-booster synchrotron are foreseen [2, 3]. The parameters of the booster cycle and the bunch pattern are driven by these pre-injectors and are presented in [4]. A summary of the parameters regarding the booster are summarised in Table 1. Because of the large number of bunches and the high bunch population the filling of the booster before acceleration is most time consuming. The total filling time for both species is then 17.25 min.

LAYOUT AND LATTICE

The layout of the booster follows the geometric footprint of the FCC hadron collider, shown in Figure 1: six short straight sections with the length of 1.4 km, which are clustered in groups of three connected by short separation arcs with the length of 3.2 km. In the middle straight sections A and G the FCC-ee collider foresees interaction regions for the two experiments. The additional experimental caverns in points F and H will only be used for injection. The FCC-ee collider rings will have a transverse offset of about 1 m to the outside. The interaction points will have an even larger offset of 10.6 m, as a result of the requirements coming from the crossing angle and synchrotron radiation mitigation around the experiments. Therefore, the booster will bypass the detectors on the inside of the cavern as shown in Figure 2. As in the case of the collider RF sections are located in the points D and J. The beam transfer from the booster to the collider is foreseen in the points B and L.

The horizontal equilibrium emittance of the beams in the booster should have a similar value than in the collider rings to prevent background resulting from the top-up injection. The length of the basic arc FODO cell was therefore chosen to be about 53 m in the separation arc and about 54 m in the long arcs. Different lengths are necessary to fit the given geometry determined by the FCC hadron collider. As for the collider the lattice of the booster is optimised for two optics: an optics with 60° phase advance per cell is used for

Table 1: Parameters of the booster cycle for full filling. The table summarises the number of bunches n_b, bunch population n_p, number of cycles required n_cycles, the cycle time of the booster t_cycle and the filling time for both species t_fill.

E / GeV	45.5	80	120	182.5
n_b	16640	2000	393	50
n_p /10^{10}	2.13	1.44	1.13	2.0
n_cycles	10	10	10	20
t_cycle / s	51.74	13.3	7.53	5.6
t_fill / s	1034.8	288	150.6	244

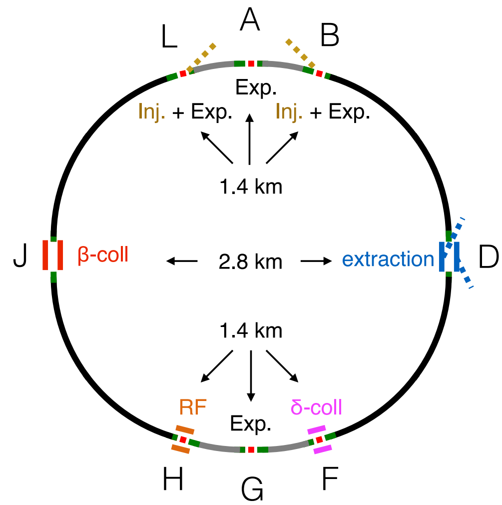

Figure 1: Layout the FCC hadron collider, which defines the geometry of the FCC main tunnel.

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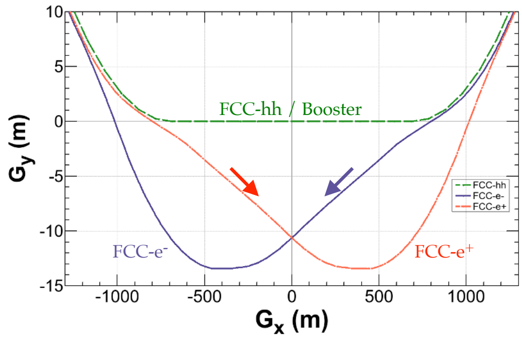

Figure 2: Geometry of the FCC-ee collider rings in the straight sections with the experiments [5]. The bypasses of the FCC-ee Booster will follow the footprint of FCC-hh.

Table 2: Horizontal equilibrium emittances of the booster compared to the values of the collider for all four beam energies. For 45.5 GeV and 80 GeV the 60° optics is used and for 120.0 GeV and 182.5 GeV optics the 90° optics.

beam energy (in GeV)	emittance booster (in nm rad)	emittance collider (in nm rad)
182.5	1.30	1.48
120.0	0.55	0.63
80.0	0.73	0.84
45.5	0.24	0.24

operation at the Z peak and the W pair production threshold (45.5 GeV and 80 GeV) and an optics with 90° phase advance per cell will be used for H production and the $t\bar{t}$ production threshold (120 GeV and 182.5 GeV). The resulting horizontal equilibrium emittances are summarised in table 2.

The curvature radius of the arcs is $R = 13.15$ km. At the beginning and at the end of each arc, a 566 metre long section is reserved for the dispersion suppressors of the hadron collider and therefore has a different curvature radius of $R = 15.06$ km. In the booster lattice 10 FODO cells with 56.6 m length and less bending strength are installed to follow the geometry. In order to avoid dipole fields smaller than in the rest of the arcs, the small bending angle is obtained with shorter dipole magnets. The quadrupoles of the last five cells are used to suppress the horizontal dispersion function and to match the optics to one of the straight FODO cells. In the straight sections around points A, B, F, G, H and L, the cell length was chosen to be 50 m to fit the geometry. In the extended straight sections around points D and J the cell length has been increased to 100 m in order to maximise the space available for RF installations. The transition of the optics from the arcs to these long FODO cells is shown in Figure 3.

Contrary to the collider "tapering" (scaling of the magnet strengths to the local beam energy) is not foreseen. As the booster is supposed to be a rapid cycling synchrotron, such scaling is not adequate because of the changing beam energy.

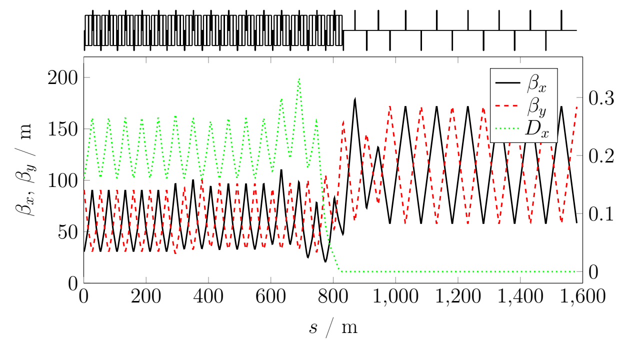

Figure 3: Beta functions and horizontal dispersion function of the transition from the arc lattice into a straight section with RF installation. The first five cells are regular arc FODO cells with a length of 54 m. The following section of 566 m consists of ten FODO cells with different bending angle to fit the geometry of the dispersion suppressor of the hadron collider. They also serve as quadrupole-based dispersion suppressor and matching section to the optics of the straight FODO cells with 100 m length.

DYNAMIC APERTURE WITH MISALIGNMENTS

Tracking studies based on the survival of the particles after 1000 turns have shown that a non-interleaved sextupole scheme provides the largest dynamic aperture (DA) for both optics. The tracking studies were performed with PTC for 20 GeV beam energy and include radiation damping and quantum excitation. Also Gaussian distributed quadrupole misalignments were introduced with a σ of 100 µm. The results for both the 60° optics and the 90° optics are presented in Figure 4: the green line shows the DA for the ideal machine. The effect of the misalignments was studied for 100 error seed. The grey lines refer to the DA after a simple orbit correction with MICADO based on the least squares theory as described in [6]. As it can be seen, the DA is not affected within the precision of the simulations. For both optics the DA is more than 200 σ in the horizontal plane. It might be noted, that the equilibrium emittance is only $\epsilon_x = 15$ pm rad, which leads to such high numbers. However, even for a larger emittance there is margin with respect to DA, because on-axis injection is foreseen. In the vertical plane the DA of the 60° optics is about twice compared to the 90° optics, where the DA is still about 700 σ.

WIGGLERS AT 20 GEV BEAM ENERGY

The beam parameters at injection energy need special consideration: the low synchrotron radiation power leads to weak radiation damping and the transverse damping time becomes longer than 10 s, which is not compatible with the foreseen booster cycle and the top-up requirements. In order to guarantee the same emittances and energy spread for all bunches at extraction the equilibrium must be reached before acceleration. With a damping time of 10 s this would require about a minute, which is too long if top-up rate needs to be

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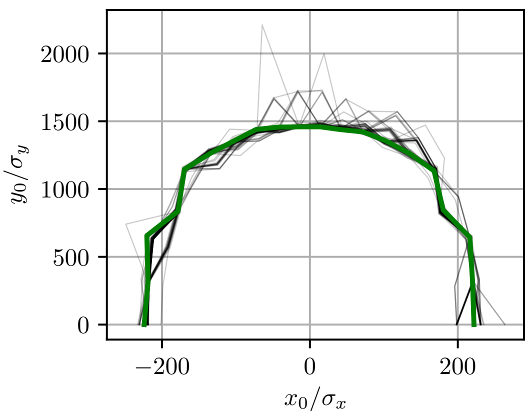
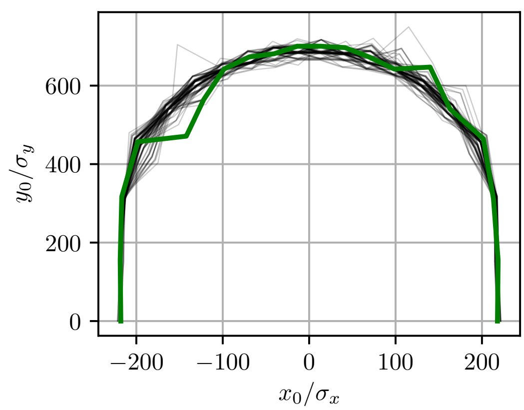


(a) 60° optics



(b) 90° optics

Figure 4: Dynamic aperture of the booster at 20 GeV injection energy with and without transverse misalignments (σ = 100 µm) of the quadrupoles. The green line refers to the ideal machine, the grey lines to 100 different error seeds after orbit correction.

about once per minute to keep the beam intensity within 5%. As mentioned earlier, the horizontal equilibrium emittance shrinks down to ϵ_x = 15 pm rad leading to emittance blow-up of a factor 48 due to intra-beam-scattering. Therefore 16 wigglers with the length of approximately 9 m are installed in the straight sections around the points A and G. The normal conducting wigglers are optimised such that a transverse damping time of $\tau_{x,y}$ = 0.1 s is reached and the emittance is increased to ϵ_x = 240 pm rad for the 60° optics and to 180 pm rad for the 90° optics, which is large enough to avoid emittance blow-up due to intra-beam-scattering. Although the wigglers are installed in dispersion free sections, the intrinsic dispersion created within the wiggler is sufficient to increase the quantum excitation. The magnetic pole tip field of the wigglers is B = 1.8 T. The pole length is 9.5 cm and the gap width is 5 cm. However, the energy loss per turn increases from U_0 = 1.3 MeV/turn to 126 MeV/turn, which needs to be compensated by the RF system. The minimum RF voltage required is V_{rf} = 140 MV. During the energy ramp-up the wigglers are switched off adiabatically to reduce the energy loss at extraction energy. As a consequence, the same RF voltage is sufficient as for the collider.

OUTLOOK

The effect of the wigglers on the dynamic aperture is under investigation. With the wigglers included a maximum value for the emittances of the injected beam can be derived, which needs to be conform with the pre-booster synchrotron. A dedicated injection and extraction section will be included.

The investigation of magnetic field errors will allow to deduce the minimum magnetic field in the dipole magnets and thus the minimum beam energy for injection. Investigations of the TMCI instability due to resistive wall are ongoing.

CONCLUSION

The FCC-ee booster synchrotron will perform continuous top-up injection in order to keep the beam intensity within 5% and therefore achieve luminosities of the order of 10^{35} cm^{-2}s^{-1}. Depending on the operation mode it will ramp up the beam energy from 20 GeV to 45.5 - 182.5 GeV. The presented lattice obtains similar emittances as the collider for the injected beam using both a 60° and a 90° optics. For the injection energy wiggler magnets are used to decrease the damping time to 0.1 s and to increase the emittance from to ϵ_x = 12 pm rad to 240 pm rad for the 60° optics and 180 pm rad for the 90° optics. This is necessary to avoid emittance blow-up due to intra-beam-scattering. Quadrupole misalignments do net reduce the DA, the effect of the wigglers are still under investigation.

ACKNOWLEDGEMENT

We would like to thank F. Antoniou for the fruitful discussions and her help with the IBS module in MAD-X.

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